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Effects of water vapor anneal on MIS devices made of nitrided gate dielectrics  
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**Abstract:**

Silicon nitride and oxynitride films are known to possess a number of attractive properties over thermal SiO<sub>2</sub> as gate dielectric for Field-Effect Transistors (FETs), including better resistance to impurity diffusion and higher dielectric constant. However, their poor interface properties have prevented their use as a mainstream gate dielectric. Even in case of nitridized oxides where the nitrogen content is minute, the reduced peak transconductance for n-channel transistors is still a major concern for many applications despite their much improved reliability. This paper shows that a modest annealing treatment in a steam furnace yields dramatic improvement of FET's transconductance as well as its current driveability for devices containing nitrided gate while preserving the excellent reliability. Only results on silicon nitride based MOS devices are included.

**Index Terms:**

MISFET; annealing; semiconductor device reliability; leakage currents; dielectric thin films; water vapor anneal; MIS devices; nitrided gate dielectrics; field-effect transistor interface properties; transconductance; steam furnace; current driveability; reliability; Si<sub>3</sub>N<sub>4</sub>

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## Effects of Water Vapor Anneal on MIS Devices Made of Nitrided Gate Dielectrics

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### Introduction

Silicon nitride and oxynitride films are known to possess a number of attractive properties over thermal  $\text{SiO}_2$  as gate dielectric for Field-Effect Transistors (FET's), including better resistance to impurity diffusion and higher dielectric constant. However, their poor interface properties have prevented their use as a mainstream gate dielectric. Even in the case of nitridized oxides where the nitrogen content is minute, the reduced peak transconductance for n-channel transistors is still a major concern for many applications, despite their much improved reliability.

This paper will show that a modest annealing treatment in a steam furnace yields dramatic improvement of FET's transconductance as well as its current driveability for devices containing nitrided gate while preserving their excellent reliability. For brevity, this summary will only include our results on silicon nitride based MNS devices.

### Experimental

The water-vapor annealing (WVA) treatments were performed in an ordinary steam oxidation furnace at various temperatures, although the results to be reported in this summary were mostly obtained at  $400^\circ\text{C}$ [1]. In principle the WVA step could be inserted most anywhere in the processing sequence after the formation of the gate dielectric; we emphasize the use of WVA as a post-metal annealing (PMA) step in this summary, although an example is given to show the effect of post-deposition WVA as well.

Thin silicon nitride films, with equivalent oxide thickness (EOT)  $\sim 5$  nm, were deposited directly on Si at room temperature by the Jet Vapor Deposition (JVD) technique [2]. To accentuate the effects of the water vapor annealing (WVA), some nitride films were deposited under non-optimized conditions. In some devices, a post-deposition anneal was done at  $800^\circ\text{C}$  for 30 min in  $\text{N}_2$ . Large-area Al-gate MNS capacitors and transistors were then fabricated. The WVA step was used either to replace the post-deposition anneal step or as a PMA step. Capacitance-Voltage (C-V), Current-Voltage (I-V), and charge pumping measurements were used to characterize the device properties before and after WVA.

### Results and Discussion

One of the major problems of the thin CVD silicon nitride film as well as non-optimized JVD silicon nitride film is

its excessive leakage current, and our results suggest that WVA may be a solution to this problem.

Curve (a) in Fig. 1 is from a MNS capacitor which had received a  $800^\circ\text{C}$  annealing in dry  $\text{N}_2$  for 30 min following the nitride deposition, while curve (b) is from a similar device except that the  $800^\circ\text{C}$  annealing step was replaced by WVA at  $520^\circ\text{C}$ . The EOT of the nitride in both cases is approximately 4.7 nm. It is obvious that the WVA treatment leads to reduced gate leakage current. In addition, our analysis has indicated that curve (a) contains a significant component of Frenkel-Poole conduction while curve (b) is typical of Fowler-Nordheim tunneling, suggesting effective removal of trap-assisted current component by the WVA.

From the corresponding quasi-static CV curves depicted in Fig. 2, one can see clearly that the interface properties of these MNS capacitors also improved significantly when the  $800^\circ\text{C}$  nitrogen anneal was replaced by a  $520^\circ\text{C}$  WVA. The capacitor represented by curve (b) in Fig. 2 was then given an additional WVA at  $400^\circ\text{C}$  as a PMA step, and the resulting C-V curves are shown in Fig. 3. The excellent match between high frequency and quasi-static CV indicates a very low density of interface traps. The flatband voltage of HFCV also indicates a low density of dielectric charge.

As expected, the transconductances of corresponding MNS-FET's also improved dramatically as a result of the WVA, as shown in Fig. 4, which is directly correlatable with the reduced densities of interface traps and dielectric charge.

Figure 5 shows that the current driveability of the MNS transistor is also increased significantly upon WVA in these same devices, which is again believed to be due to the reduced densities of interface traps and dielectric charge.

It should be noted that WVA was also performed on a set of control devices with thermal  $\text{SiO}_2$  as the gate dielectric, and no effect could be detected.

An obvious concern of the WVA process is whether it introduces reliability problems. While much more comprehensive study must be conducted to address this issue, our preliminary study has revealed no degradation of hot-carrier reliability resulting from WVA, either in terms of hot-carrier induced interface-trap generation, transconductance degradation, or threshold voltage shift.

Figure 6 compares the charge trapping characteristics between two MNS capacitors of basically identical EOT ( $\sim 4.6\text{nm}$ ) under constant-current stress. The lower curve is from a sample that did not receive WVA, while the upper curve is from a sample that came from the same wafer except that it had been treated by WVA. Two features are worth noting: (1) It takes a higher gate voltage for the WVA'd sample to maintain the same current level, due to the lower gate current at a given gate voltage, which is consistent with the data in Fig.1, and (2) Both show electron trapping characteristic, but the WVA'd sample exhibits a lower voltage shift (21 mV vs 32 mV) after the same electron fluence of  $0.4\text{ C/cm}^2$ . Both features noted above suggest the possibility that the WVA step may actually improve the reliability of MNS devices, although much more work is needed before a credible conclusion can be reached.

It is puzzling why WVA should work as it does, as we know annealing either in hydrogen or in oxygen (the two chemical components in water vapor) at comparable temperatures does not work, nor does sequential annealing involving the

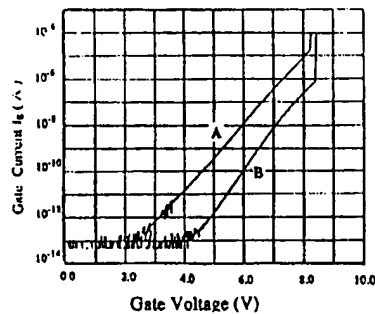


Fig.1 I-V characteristics from MNS capacitors with JVD nitride as the gate dielectric. (a) before WVA treatment; (b) After WVA treatment.

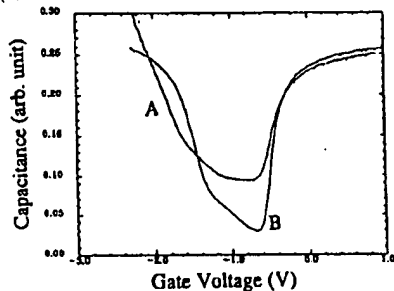


Fig.2 Quasi-static C-V curves of MNS capacitors. Curve A: without post-deposition WVA treatment; Curve B: with WVA treatment.

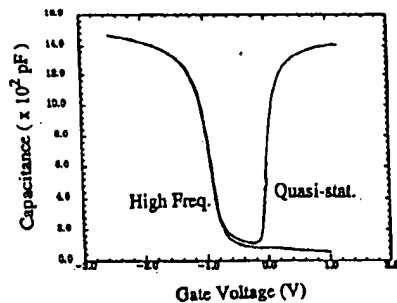


Fig.3 Additional WVA at  $450^\circ\text{C}$  as a PMA step on curve (B) in Fig.2 resulted in further improved C-V characteristic.

two. We also noticed that WVA does not improve the properties of conventional thermal oxide devices, despite its dramatic effects on silicon nitride and its interfaces, as well as polycrystalline silicon based TFT devices that contain a deposited oxide as the gate dielectric [3]. The understanding of the WVA mechanism will be an important task along with further development of the WVA technology.

#### Acknowledgement

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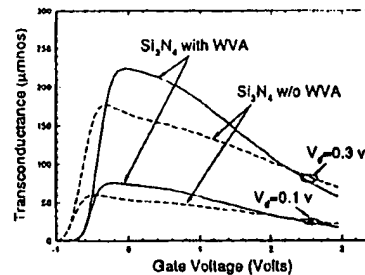


Fig.4 Transconductances for MNSFET before and after WVA for  $V_D=0.1\text{v}$  and  $0.3\text{v}$ . EOT  $\sim 5.5\text{nm}$ . Device area:  $50 \times 200\mu\text{m}$ .

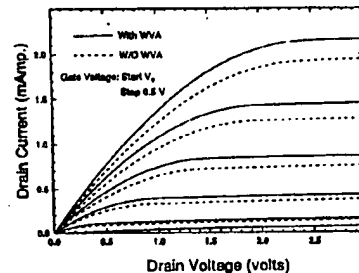


Fig.5 Current driveability is also increased dramatically with WVA.

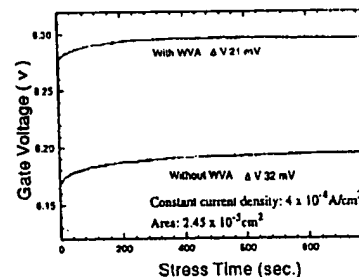


Fig.6 A comparison of the trapping characteristics between two capacitors with and without WVA treatment.